Global analysis of NSI in exclusive semileptonic tau decays

XIX Mexican School of Particles and Fields

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CINVESTAV

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[1] S. González-Solís, A. Miranda, J. R and P. Roig, Phys. Lett. B **804**, 135371 (2020).

Overview

Motivation

Motivation to do this study

- The main motivation to do this work was to probe that semileptonic tau decays are really important in complementing traditional low-energy probes such as nuclear β decays, semileptonic pion and kaon decays, and also high energy measurements at the LHC.
- Show the importance of semileptonic tau decays as golden modes at Belle-II.

Theoretical framework

Effective Field Theories

$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \cdots$$

Effective theory analysis of $\tau^- \to \nu_\tau \bar{u} D$ $(D = d, s)$

The effective lagrangian density constructed with dimension six operators and invariant under the $SU(2)_L \otimes U(1)$ group has the following form,

$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i \alpha_i O_i \qquad (1)$$

Effective theory analysis of $\tau^- \to \nu_\tau \bar{u} D$ ($D = d, s$)

We can explicitly construct the low-scale O(1GeV) effective lagrangian for semi-leptonic transitions as follows: [2] [3]:

$$
\begin{aligned}
\mathcal{L}_{CC} \;=\; & -\frac{G_F V_{uD}}{\sqrt{2}}\Big[(1+\epsilon_L^\tau)\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau\cdot\bar{u}\gamma^\mu(1-\gamma^5)D \\
& +\epsilon_R^\tau\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau\cdot\bar{u}\gamma^\mu(1+\gamma^5)D \\
& +\bar{\tau}(1-\gamma^5)\nu_\tau\cdot\bar{u}(\epsilon_S^\tau-\epsilon_P^\tau\gamma^5)D \\
& +\epsilon_T^\tau\bar{\tau}\sigma_{\mu\nu}(1-\gamma^5)\nu_\tau\,\bar{u}\sigma^{\mu\nu}(1-\gamma^5)D\Big]+h.c.\,, \qquad (2)
\end{aligned}
$$

[2] T. Bhattacharya, V. Cirigliano, S. D. Cohen, A. Filipuzzi, M. Gonzalez-Alonso, M. L. Graesser, R. Gupta and H. W. Lin, Phys. Rev. D **85**, 054512 (2012).

[3] S. González-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Lett. B **804**, 135371 (2020).

One-meson decay modes $\tau^- \to P^- \nu_\tau$ ($P = \pi, K$).

$$\Gamma(\tau^- \to \pi^- \nu_\tau) = \frac{G_F^2 |\tilde{V}_{ud}^e|^2 f_\pi^2 m_\tau^3}{16\pi} \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 \times \left(1 + \delta_{\rm em}^{\tau\pi} + 2\Delta^{\tau\pi} + \mathcal{O}(\epsilon_i^\tau)^2 + \mathcal{O}(\delta_{\rm em}^{\tau\pi}\epsilon_i^\tau)\right), \tag{3}$$

where f_π is the pion decay constant, the quantity $\delta_{\rm em}^{\tau\pi}$ accounts for the EM radiative corrections and the term $\Delta^{\tau\pi}$ contains the tree-level NP corrections that arise from $\mathcal{L}_{eff}$ that are not absorbed in $\tilde{V}_{ud}^e$.

One-meson decay modes $\tau^- \to P^- \nu_\tau$ ($P = \pi, K$).

The product $G_F V_{uD}$ in $\mathcal{L}_{eff}$ denotes that its determination from the superallowed nuclear Fermi β decays carries implicitly a dependence on ϵ_L^e and ϵ_R^e that is given by [4]

$$G_F \tilde{V}^e_{uD} = G_F \left(1 + \epsilon_L^e + \epsilon_R^e\right) V_{uD} \,, \tag{4}$$

For the channel $\tau^- \to K^- \nu_\tau$, the decay rate is that of Eq. (3) but replacing $\tilde{V}^e_{ud} \to \tilde{V}^e_{us}$, $f_\pi \to f_K$, $m_\pi \to m_K$, and $\delta_{\rm em}^{\tau\pi}$ and $\Delta^{\tau\pi}$ by $\delta_{\rm em}^{\tau K}$ and $\Delta^{\tau K}$, respectively.

[4] M. González-Alonso and J. Martin Camalich, JHEP **12**, 052 (2016)

Amplitude for two-meson decay modes $\tau^- \to (PP')^- \nu_\tau$

$$
\begin{aligned}
\mathcal{M} &= \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T \\
&= \frac{G_F V_{uD} \sqrt{S_{EW}}}{\sqrt{2}} (1 + \epsilon_L + \epsilon_R) \\
&\quad \times \left[L_\mu H^\mu + \hat{\epsilon}_S L H + 2 \hat{\epsilon}_T L_{\mu\nu} H^{\mu\nu} \right] , \qquad (5)
\end{aligned}
$$

where the leptonic currents are defined by:

$$
\begin{aligned}
L_\mu &= \bar{u}(P') \gamma_\mu (1 - \gamma^5) u(P) , \qquad (6) \\
L &= \bar{u}(P') (1 + \gamma^5) u(P) , \qquad (7) \\
L_{\mu\nu} &= \bar{u}(P') \sigma_{\mu\nu} (1 + \gamma^5) u(P) . \qquad (8)
\end{aligned}
$$

Amplitude for two-meson decay modes $\tau^- \to (PP')^- \nu_\tau$

and where the hadronic matrix elements are given by

$$H = \langle K^- K^0 | \bar{d} u | 0 \rangle = F_S^{K^- K^0}(s) \, , \tag{9}$$

$$H^\mu = \langle K^- K^0 | \bar{d} \gamma^\mu u | 0 \rangle = C^V_{K^- K^0} Q^\mu F_+^{K^- K^0}(s) + C^S_{K^- K^0} \left(\frac{\Delta_{KK}}{s} \right) q^\mu F_0^{K^- K^0}(s) \, , \tag{10}$$

$$H^{\mu\nu} = \langle K^- K^0 | \bar{d} \sigma^{\mu\nu} u | 0 \rangle = i F_T^{K^- K^0}(s) (p^\mu_{K^0} p^\nu_K - p^\mu_K p^\nu_{K^0}) \, , \tag{11}$$

Two-meson Form Factors

$$F_+^{\pi\pi}(s) = \exp\left[\alpha_1 s + \frac{\alpha_2}{2}s^2 + \frac{s^3}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{\delta_1^1(s')}{(s')^3(s'-s-i0)}\right], \quad (12)$$

[5] [6] [7]

[5] S. Gonzàlez-Solís and P. Roig, Eur. Phys. J. C **79** (2019) no.5, 436.
[6] A. Pich and J. Portolés, Phys. Rev. D **63** (2001), 093005.
[7] D. Gómez Dumm and P. Roig, Eur. Phys. J. C **73** (2013) no.8, 2528.

Two-meson Form Factors

$$F_+^{K\pi}(s) = \exp\left[\alpha_1 s + \frac{\alpha_2}{2}s^2 + \int_{s_{\pi K}}^{\infty} ds' \frac{\delta_1^{1/2}(s)}{(s')^3(s'-s-i\epsilon)}\right] , \quad (13)$$

[8] [9] [10]

[8] D. R. Boito, R. Escribano and M. Jamin, Eur. Phys. J. C **59** (2009) 821.

[9] D. R. Boito, R. Escribano and M. Jamin, JHEP **1009** (2010) 031.

[10] R. Escribano, S. González-Solís, M. Jamin and P. Roig, JHEP **1409** (2014) 042.

Two-meson form factors

For the scalar form factors we also take advantage from previous literature, for the $F_0^{\pi\pi}(s)$ we use [11], for the $F_0^{KK}(s)$ we use [12] [13] [14] and for $F_0^{K\pi}(s)$ and $F_0^{K\eta^{(\prime)}}(s)$ we use [15]

[11] S. Descotes-Genon and B. Moussallam, Eur. Phys. J. C **74**, 2946 (2014).
[12] Z. H. Guo and J. A. Oller, Phys. Rev. D **84**, 034005 (2011).
[13] Z. H. Guo, J. A. Oller and J. Ruiz de Elvira, Phys. Rev. D **86**, 054006 (2012).
[14] Z. H. Guo, L. Liu, U. G. Meißner, J. A. Oller and A. Rusetsky, Phys. Rev. D **95**, no.5, 054004 (2017).
[15] M. Jamin, J. A. Oller and A. Pich, Nucl. Phys. B **622**, 279-308 (2002).

Tensor form factors

For the tensor form factors $F_T^{PP'}(s)$ we have[16] [17],

$$F_T^{PP'}(s) = F_T^{PP'}(0) \exp\left[\frac{s}{\pi}\int_{s_{\rm th}}^{s_{\rm cut}} \frac{ds'}{s'} \frac{\delta_T^{PP'}(s')}{(s'-s-i0)}\right] , \qquad (14)$$

where $s_{\rm th}$ is the two-meson production threshold for the lightest pair of mesons with the same quantum numbers as the given pair PP'.
$F_T^{PP'}(0)$: ChPT with Tensor Sources+Lattice

[16] O. Cata and V. Mateu, JHEP **0709**, 078 (2007).
[17] I. Baum, V. Lubicz, G. Martinelli, L. Orifici and S. Simula, Phys. Rev. D **84**, 074503 (2011).

Two-meson decay modes $\tau^- \to (PP')^- \nu_\tau$.

$$\frac{d\Gamma}{ds} = \frac{G_F^2 |\tilde{V}_{uD}^e|^2 m_\tau^3 S_{EW}}{384\pi^3 s} \left(1 - \frac{s}{m_\tau^2}\right)^2 \lambda^{1/2}(s, m_P^2, m_{P'}^2)$$

$$\times \Big[(1 + 2(\epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e)) X_{VA}$$

$$+ \epsilon_S^\tau X_S + \epsilon_T^\tau X_T + (\epsilon_S^\tau)^2 X_{S^2} + (\epsilon_T^\tau)^2 X_{T^2} \Big], \qquad (15)$$

18 19 20 21 22

[18] E. A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, JHEP **12**, 027 (2017).

[19] J. A. Miranda and P. Roig, JHEP **11**, 038 (2018).

[20] J. Rendón, P. Roig and G. Toledo Sánchez, Phys. Rev. D **99**, no.9, 093005 (2019).

[21] S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Rev. D **101**, no.3, 034010 (2020).

[22] S. Gonzàlez-Solís, A. Miranda, J. Rendón and P. Roig, Phys. Lett. B **804**, 135371 (2020).

Two-meson decay modes $\tau^- \to (PP')^- \nu_\tau$.

$$\begin{aligned}
X_{VA} &= \frac{1}{2s^2}\Big\{3\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \Delta^2_{PP'} \\
&\quad + \left(C^V_{PP'}\right)^2 |F_+^{PP'}(s)|^2 \left(1+\frac{2s}{m_\tau^2}\right)\lambda(s, m_P^2, m_{P'}^2)\Big\}, \\
X_S &= \frac{3}{s\, m_\tau}\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \frac{\Delta^2_{PP'}}{m_d - m_u}, \\
X_T &= \frac{6}{s\, m_\tau} C^V_{PP'} \,\mathrm{Re}\big[F_T^{PP'}(s)\big(F_+^{PP'}(s)\big)^*\big]\lambda(s, m_P^2, m_{P'}^2), \\
X_{S^2} &= \frac{3}{2\, m_\tau^2}\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \frac{\Delta^2_{PP'}}{(m_d - m_u)^2}, \\
X_{T^2} &= \frac{4}{s}|F_T^{PP'}(s)|^2\left(1+\frac{s}{2\, m_\tau^2}\right)\lambda(s, m_P^2, m_{P'}^2), \qquad (16)
\end{aligned}$$

Global analysis

New Physics bounds from $\Delta S = 0$ decays

from the $\tau^- \to \pi^- \nu_\tau$ decay rate alone, we obtain the following constraint,

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_\pi^2}{m_\tau(m_u + m_d)}\epsilon_P^\tau = (-0.12 \pm 0.68) \times 10^{-2}\,, \quad (17)$$

Input: $f_\pi = 130.2(8)$ (FLAG)[23]; $\delta_{em}^{\tau\pi} = 1.92(24)\%$[24][25][26];
$|\tilde{V}_{ud}^e| = 0.97420(21)$ (β decays, PDG).

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[23] S. Aoki *et al.* [Flavour Lattice Averaging Group], Eur. Phys. J. C **80**, no.2, 113 (2020).

[24] R. Decker and M. Finkemeier, Nucl. Phys. B **438**, 17-53 (1995).

[25] V. Cirigliano and I. Rosell, JHEP **10**, 005 (2007).

[26] J. L. Rosner, S. Stone and R. S. Van de Water, [arXiv:1509.02220 [hep-ph]].

New Physics bounds from $\Delta S = 0$ decays

The bounds for the non-SM effective couplings resulting from the global fit are found to be (in the $\overline{\mathrm{MS}}$ scheme at scale $\mu = 2$ GeV)

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_\pi^2}{2m_\tau(m_u+m_d)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 0.6^{+2.3}_{-1.8}{}^{+0.2}_{-0.1} \pm 0.4 \\ 0.3 \pm 0.5^{+1.1}_{-0.9}{}^{+0.1}_{-0.0} \pm 0.2 \\ 9.7^{+0.5}_{-0.6} \pm 21.5\,{}^{+0.0}_{-0.1} \pm 0.2 \\ -0.1 \pm 0.2^{+1.1}_{-1.4}{}^{+0.0}_{-0.1} \pm 0.2 \end{pmatrix} \times 10^{-2}, \tag{18}$$

27 1.stat. fit uncertainty, 2.pion VFF, 3.quark masses, 4.TFF

[27] if we use the $\pi\eta$ channel we reproduce the limits in E. A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, JHEP **12**, 027 (2017).

New Physics bounds from $|\Delta S| = 1$ decays

from the $\tau^- \to K^- \nu_\tau$ decay rate alone, we obtain the following constraint,

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_K^2}{m_\tau(m_u + m_s)} \epsilon_P^\tau = (-0.41 \pm 0.93) \times 10^{-2} \,. \quad (19)$$

Input: $f_K = 155.7(7)$ (FLAG)[28]; $\delta_{em}^{\tau K} = 1.98(31)\%$[29] [30][31];
$|\tilde{V}_{us}^e| = 0.2231(7)$ (PDG).

[28] S. Aoki *et al.* [Flavour Lattice Averaging Group], Eur. Phys. J. C **80**, no.2, 113 (2020).

[29] R. Decker and M. Finkemeier, Nucl. Phys. B **438**, 17-53 (1995).

[30] V. Cirigliano and I. Rosell, JHEP **10**, 005 (2007).

[31] J. L. Rosner, S. Stone and R. S. Van de Water, [arXiv:1509.02220 [hep-ph]].

New Physics bounds from $|\Delta S| = 1$ decays

In this case, the limits for the NP effective couplings are found to be (in the $\overline{\mathrm{MS}}$ scheme at scale $\mu = 2$ GeV)

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_K^2}{2m_\tau(m_u+m_s)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 1.5 \pm 0.3 \\ 0.4 \pm 0.9 \pm 0.2 \\ 0.8^{+0.8}_{-0.9} \pm 0.3 \\ 0.9 \pm 0.7 \pm 0.4 \end{pmatrix} \times 10^{-2}, \quad (20)$$

1.stat. fit uncertainty, 2.TFF

Updates

with the updated radiative corrections in [32]

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_\pi^2}{m_\tau(m_u + m_d)} \epsilon_P^\tau = -(0.15 \pm 0.72) \times 10^{-2}. \quad (21)$$

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_K^2}{m_\tau(m_u + m_s)} \epsilon_P^\tau = -(0.36 \pm 1.18) \times 10^{-2}. \quad (22)$$

$\Gamma(W \to \tau\nu_\tau)/\Gamma(W \to \mu\nu_\mu) \to |g_\tau/g_\mu| = 0.995 \pm 0.006$ [33]

[32] M. A. Arroyo-Ureña, G. Hernández-Tomé, G. López-Castro, P. Roig and I. Rosell, [arXiv:2107.04603 [hep-ph]].

[33] [CMS], CMS-PAS-SMP-18-011.

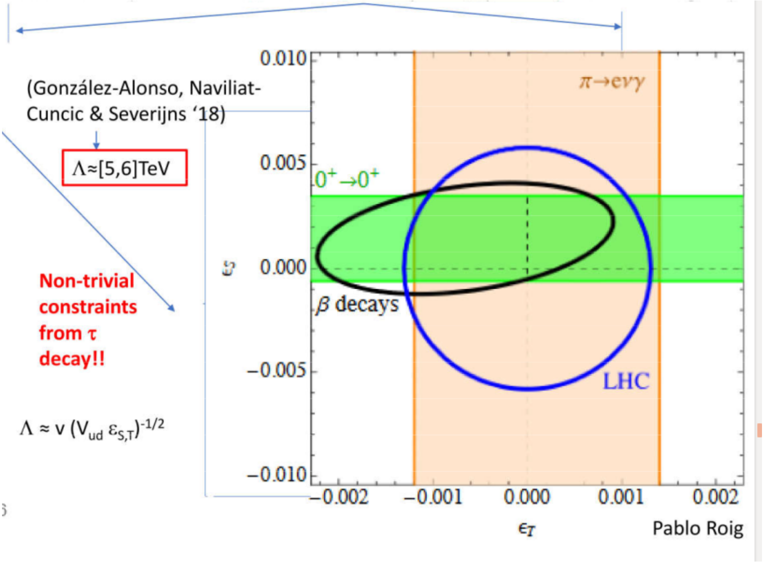
New Physics bounds from a global fit to both $\Delta S = 0$ and $|\Delta S| = 1$

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} =$$

$$\begin{pmatrix} 2.9 & \pm 0.6 & {}^{+1.0}_{-0.9} & \pm 0.6 & \pm 0.0 & \pm 0.4 & {}^{+0.2}_{-0.3} \\ 7.1 & \pm 4.9 & {}^{+0.5}_{-0.4} & {}^{+1.3}_{-1.5} & {}^{+1.2}_{-1.3} & \pm 0.2 & {}^{+40.9}_{-14.1} \\ -7.6 & \pm 6.3 & \pm 0.0 & {}^{+1.9}_{-1.6} & {}^{+1.7}_{-1.6} & \pm 0.0 & {}^{+19.0}_{-53.6} \\ 5.0 & {}^{+0.7}_{-0.8} & {}^{+0.8}_{-1.3} & {}^{+0.2}_{-0.1} & \pm 0.0 & \pm 0.2 & {}^{+1.1}_{-0.6} \\ -0.5 & \pm 0.2 & {}^{+0.8}_{-1.0} & \pm 0.0 & \pm 0.0 & \pm 0.6 & \pm 0.1 \end{pmatrix} \times 10^{-2}, \quad (23)$$

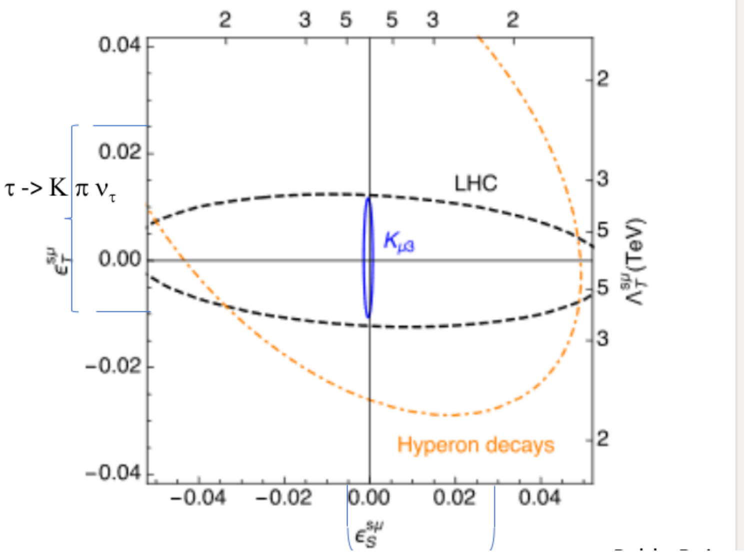
1.stat. fit uncertainty, 2.pion VFF, 3.CKM parameters, 4.rad. cor., 5.TFF, 6.quark masses

Comparison between different probes for the ϵ's



It is important to remerber the result G. Aad *et al.* [ATLAS], [arXiv:2007.14040 [hep-ex].

Comparison between different probes for the ϵ's



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[34] M. González-Alonso and J. Martín Camalich, JHEP **1612**, 052 (2016).

Conclusions

Conclusions

- This work highlights that hadronic tau lepton decays remain to be not only a privileged tool for the investigation of the hadronization of QCD currents but also offer an interesting scenario as New Physics probes.
- In general, our bounds on the NP couplings, are competitive. This is specially the case for the combination of couplings $\epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e$, which is found to be in accord with [35] and ϵ_T^τ, that can even compete with the constraints set by the theoretically cleaner $K_{\ell 3}$ decays.
- As for ϵ_S^τ, it is impossible to compete with the limits coming from $K_{\ell 3}$ decays (the decay $\tau^- \to \pi^- \eta \nu_\tau$ has not been taken into account because the lack of data).

[35] V. Cirigliano, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, Phys. Rev. Lett. **122**, no.22, 221801 (2019).

Conclusions

- $\tau \to \pi\eta\nu_\tau$ is good constraining ϵ_S but is limited due to lack of data.
- $\tau \to \pi\pi\nu_\tau$ and $\tau \to \pi K\nu_\tau$ are good constraining ϵ_T.
- We have performed the first global analysis for $|\Delta S| = 1$ in the tau sector.

Thank you!

Tau Physics (Backup)

- Provides a clean enviroment to study low energy QCD effects
- It is important in the searches for lepton flavor violation
- Important in the determination of V_{us} to complement $K_{\ell 3}$ decays and in the determination of α_S
- Important in the studies of lepton universality
- Important in the searches for new physics
- Important for providing an independent evaluation of $a_\mu^{HVP,LO}$

Important Data (Backup)

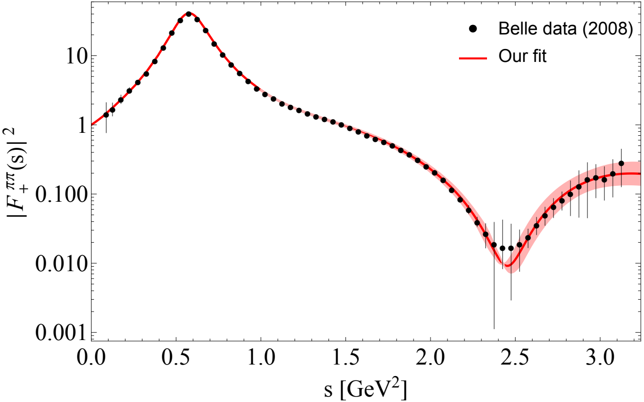

Figure: Belle measurement of the modulus squared of the pion vector form factor as compared to our fits .

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[36] M. Fujikawa *et al.* [Belle], Phys. Rev. D **78**, 072006 (2008)
[37] S. González-Solís and P. Roig, Eur. Phys. J. C **79**, no.5, 436 (2019)

Important Data

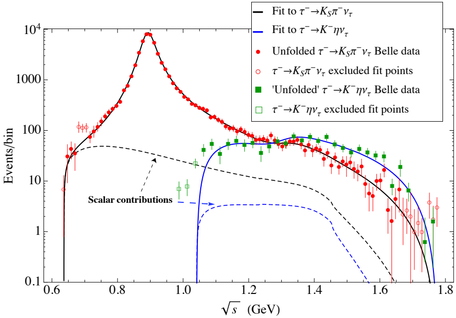

Figure: Belle $\tau^- \to K_S\pi^-\nu_\tau$ (red circles) and $\tau^- \to K^-\eta\nu_\tau$ (green squares) measurements as compared to our best fit results in (solid black and blue lines) obtained from a combined fit to both data sets. The small scalar contributions are represented by black and blue dashed lines.

38 39 40

[38] D. Epifanov *et al.* [Belle], Phys. Lett. B **654**, 65-73 (2007)

[39] K. Inami *et al.* [Belle], Phys. Lett. B **672**, 209-218 (2009)

[40] R. Escribano, S. González-Solís, M. Jamin and P. Roig, JHEP **09**, 042 (2014).

Tensor form factors

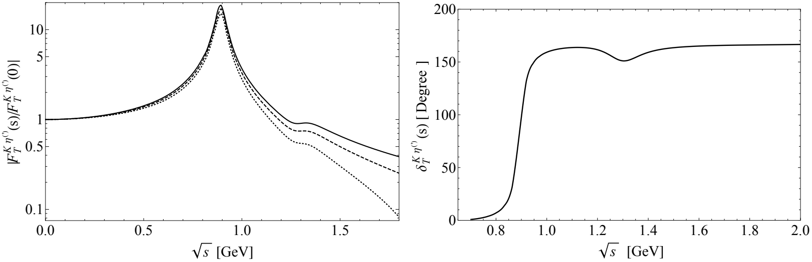

Figure: Normalized absolute value of the tensor form factor $F_T^{K\eta^{(\prime)}}(s)$ (left), for $s_{\rm cut} = 4$ GeV^2 (dotted line), 9 GeV^2 (dashed line) and $s_{\rm cut} \to \infty$ (solid line), and tensor form factor phase $\delta_T^{K\eta^{(\prime)}}(s)$ (right).

Tensor form factors

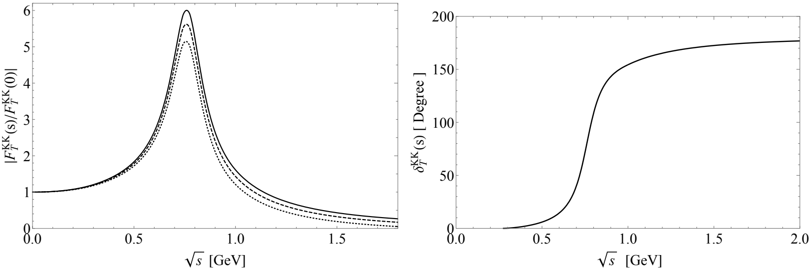

Figure: Normalized absolute value of the tensor form factor $F_T^{KK}(s)$ (left), for $s_{\mathrm{cut}} = 4$ GeV^2 (dotted line), 9 GeV^2 (dashed line) and $s_{\mathrm{cut}} \to \infty$ GeV^2 (solid line), and tensor form factor phase $\delta_T^{KK}(s)$ (right).

Tensor form factors

For the tensor form factors $F_T^{PP'}(s)$ we have[41 42],

$$F_T^{PP'}(s) = F_T^{PP'}(0) \exp\left[\frac{s}{\pi}\int_{s_{\rm th}}^{s_{\rm cut}} \frac{ds'}{s'} \frac{\delta_T^{PP'}(s')}{(s'-s-i0)}\right], \qquad (24)$$

where $s_{\rm th}$ is the two-meson production threshold for the lightest pair of mesons with the same quantum numbers as the given pair PP' and we have the normalizations,

$$F_T^{K^-\eta}(0) = \left(\frac{C_q}{\sqrt{2}} + C_s\right)\frac{\Lambda_2}{F_\pi^2}, \qquad (25)$$

$$F_T^{K^-\eta'}(0) = \left(\frac{C_q'}{\sqrt{2}} - C_s'\right)\frac{\Lambda_2}{F_\pi^2}, \qquad (26)$$

$$F_T^{K^-K^0}(0) = \frac{\Lambda_2}{F_\pi^2}. \qquad (27)$$

[41] O. Cata and V. Mateu, JHEP **0709**, 078 (2007).

[42] I. Baum, V. Lubicz, G. Martinelli, L. Orifici and S. Simula, Phys. Rev. D **84**, 074503 (2011).

Two-meson Form Factors

For the $K\eta^{(\prime)}$ case we have [43],

$$F_+^{K\eta^{(\prime)}}(s) = \cos\theta_P(\sin\theta_P)F_+^{K\pi}(s)\,, \tag{28}$$

where, $\theta_P = (-13.3 \pm 0.5)^\circ$ [44]
and [45],

$$\begin{aligned} F_+^{K\pi}(s) &= F_+^{K\pi}(0)\exp\left[\alpha_1 \frac{s}{m_\pi^2} + \frac{1}{2}\alpha_2 \frac{s^2}{m_\pi^4}\right. \\ &+ \left.\frac{s^3}{\pi}\int_{s_{K\pi}}^{s_{\rm cut}} ds' \frac{\delta_+^{K\pi}(s')}{(s')^3(s'-s-i0)}\right]\,, \end{aligned} \tag{29}$$

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[43] R. Escribano, S. Gonzalez-Solis and P. Roig, JHEP **10**, 039 (2013).
[44] F. Ambrosino *et al.* [KLOE], Phys. Lett. B **648**, 267-273 (2007).
[45] D. R. Boito, R. Escribano and M. Jamin, Eur. Phys. J. C **59**, 821-829 (2009).

Two-meson form factors

For the $K\bar{K}$ case we have [46]

$$F_+^{KK}(s) = \exp\left[\tilde{\alpha}_1 s + \frac{\tilde{\alpha}_2}{2}s^2 + \frac{s^3}{\pi}\int_{4m_\pi^2}^{s_{\rm cut}} ds' \frac{\delta_+^{KK}(s)}{(s')^3(s'-s-i0)}\right], \tag{30}$$

[46] S. Gonzàlez-Solís and P. Roig, Eur. Phys. J. C **79**, no.5, 436 (2019),

Global analysis for $\Delta S = 0$ decays

- the high-statistics $\tau^- \to \pi^-\pi^0\nu_\tau$ experimental data reported by the Belle collaboration, including both the normalized unfolded spectrum and the branching ratio.
- the branching ratio for the decay $\tau^- \to K^-K^0\nu_\tau$.
- the branching ratio for $\tau^- \to \pi^-\nu_\tau$.

The χ^2 function that is minimized in our fits is

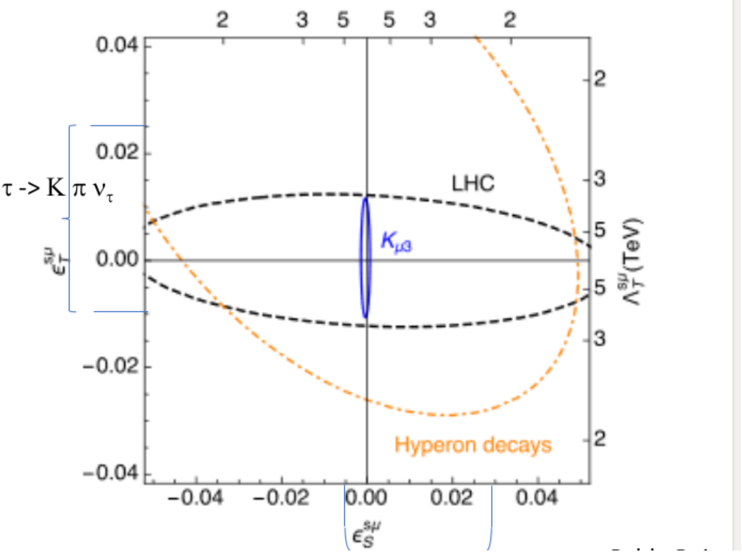
$$\chi^2 = \sum_k \left(\frac{\bar{N}_k^{\rm th} - \bar{N}_k^{\rm exp}}{\sigma_{\bar{N}_k^{\rm exp}}}\right)^2 + \left(\frac{BR_{\pi\pi}^{\rm th} - BR_{\pi\pi}^{\rm exp}}{\sigma_{BR_{\pi\pi}^{\rm exp}}}\right)^2 + \left(\frac{BR_{KK}^{\rm th} - BR_{KK}^{\rm exp}}{\sigma_{BR_{KK}^{\rm exp}}}\right)^2 + \left(\frac{BR_{\tau\pi}^{\rm th} - BR_{\tau\pi}^{\rm exp}}{\sigma_{BR_{\tau\pi}^{\rm exp}}}\right)^2 , \quad (31)$$

Global analysis for $\Delta S = 1$ decays

- the $\tau^- \to K_S \pi^- \nu_\tau$ Belle spectrum together with the measured branching ratio, $BR_{K\pi}^{\rm exp} = 0.404(2)(13)\%$.
- the branching ratio of the decay $\tau^- \to K^- \eta \nu_\tau$ ($BR_{K\eta}^{\rm exp} = 1.55(8) \times 10^{-4}$) .
- the branching ratio of the decay $\tau^- \to K^- \nu_\tau$ ($BR_{\tau K}^{\rm exp} = 6.96(10) \times 10^{-3}$).

$$\chi^2 = \sum_k \left(\frac{\bar{N}_k^{\rm th} - \bar{N}_k^{\rm exp}}{\sigma_{\bar{N}_k^{\rm exp}}} \right)^2 + \left(\frac{BR_{K\pi}^{\rm th} - BR_{K\pi}^{\rm exp}}{\sigma_{BR_{K\pi}^{\rm exp}}} \right)^2 + \left(\frac{BR_{K\eta}^{\rm th} - BR_{K\eta}^{\rm exp}}{\sigma_{BR_{K\eta}^{\rm exp}}} \right)^2 + \left(\frac{BR_{\tau K}^{\rm th} - BR_{\tau K}^{\rm exp}}{\sigma_{BR_{\tau K}^{\rm exp}}} \right)^2 , \tag{32}$$

Límites para $\hat{\epsilon}_S$ y $\hat{\epsilon}_T$



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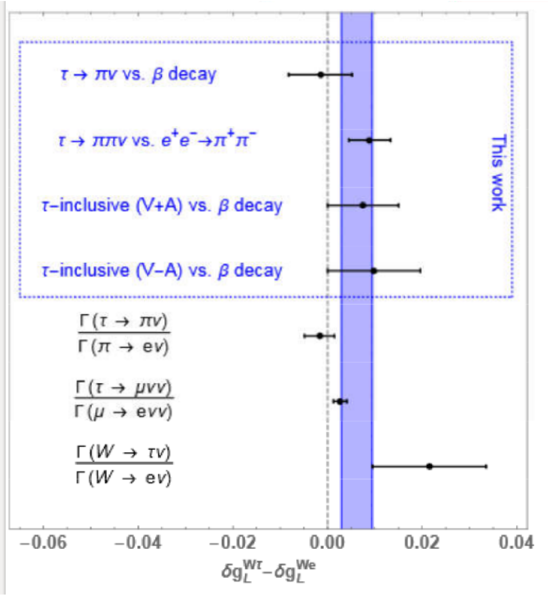
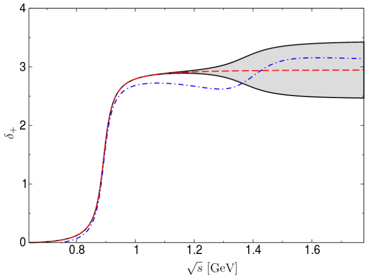
[47] M. González-Alonso and J. Martín Camalich, JHEP **1612**, 052 (2016).

$a_\mu^{HVP,LO}$ anomaly?



Inelasticidades

Estimación de inelasticidades en la fase del TFF [48]



[48] V. Cirigliano, A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **120**, no. 14, 141803 (2018)

Lagrangiano efectivo

$$\mathcal{L}_{cc} = \frac{-4G_F}{\sqrt{2}} V_{us} \Big[(1 + [v_L]_{\ell\ell}) \bar{\ell}_L \gamma_\mu \nu_{\ell L} \bar{u}_L \gamma^\mu s_L + [v_R]_{\ell\ell} \bar{\ell}_L \gamma_\mu \nu_{\ell L} \bar{u}_R \gamma^\mu s_R$$
$$+ [s_L]_{\ell\ell} \bar{\ell}_R \nu_{\ell L} \bar{u}_R s_L + [s_R]_{\ell\ell} \bar{\ell}_R \nu_{\ell L} \bar{u}_L s_R$$
$$+ [t_L]_{\ell\ell} \bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L} \bar{u}_R \sigma^{\mu\nu} s_L \Big] + \mathrm{h.c.}\,,$$

Operators

$$
\begin{aligned}
O_{lq}^{(3)} &= (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q) \\
O_{qde} &= (\bar{\ell}e)(\bar{d}q) + \text{h.c.} \\
O_{lq} &= (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \\
O_{lq}^t &= (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}
\end{aligned}
$$

and vertex corrections

$$
\begin{aligned}
O_{\varphi\varphi} &= i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}\ , \\
O_{\varphi q}^{(3)} &= i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q) + \text{h.c.}.
\end{aligned}
$$

Operators

$$O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{l}\gamma_{\mu}\sigma^{a}l) \tag{60a}$$

$$O_{\varphi l}^{(3)} = i(\varphi^{\dagger}D^{\mu}\sigma^{a}\varphi)(\bar{l}\gamma_{\mu}\sigma^{a}l) + \text{h.c.}\ . \tag{60b}$$

In terms of the coefficients of the above operators, the low-energy effective couplings appearing in $\mathcal{L}_{\rm CC}$ (see Eq. 2) are given by

$$V_{ij} \cdot [v_L]_{\ell\ell ij} = 2\,V_{ij}\left[\hat{\alpha}_{\varphi l}^{(3)}\right]_{\ell\ell} + 2\,V_{im}\left[\hat{\alpha}_{\varphi q}^{(3)}\right]_{jm}^{*} - 2\,V_{im}\left[\hat{\alpha}_{lq}^{(3)}\right]_{\ell\ell mj} \tag{61a}$$

$$V_{ij} \cdot [v_R]_{\ell\ell ij} = -\left[\hat{\alpha}_{\varphi\varphi}\right]_{ij} \tag{61b}$$

$$V_{ij} \cdot [s_L]_{\ell\ell ij} = -\left[\hat{\alpha}_{lq}\right]_{\ell\ell ji}^{*} \tag{61c}$$

$$V_{ij} \cdot [s_R]_{\ell\ell ij} = -V_{im}\left[\hat{\alpha}_{qde}\right]_{\ell\ell jm}^{*} \tag{61d}$$

$$V_{ij} \cdot [t_L]_{\ell\ell ij} = -\left[\hat{\alpha}_{lq}^{t}\right]_{\ell\ell ji}^{*}\ . \tag{61e}$$

Dalitz plots

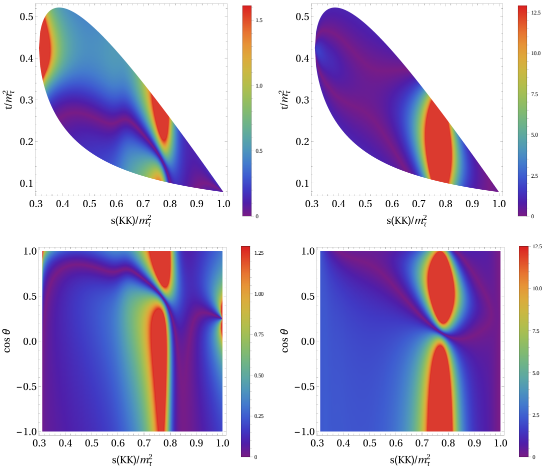


Figure: Dalitz plot distribution of $\widetilde{\Delta}\left(\hat{\epsilon}_S, \hat{\epsilon}_T\right)$ for $\tau^- \to K^- K^0 \nu_\tau$ with $(\hat{\epsilon}_S = 0.10, \hat{\epsilon}_T = 0)$ (left panels) and $(\hat{\epsilon}_S = 0, \hat{\epsilon}_T = 0.9)$ (right panels). The lower row show the differential decay distribution in the $(s, \cos\theta)$ variables.

Forward-Backward asymmetries

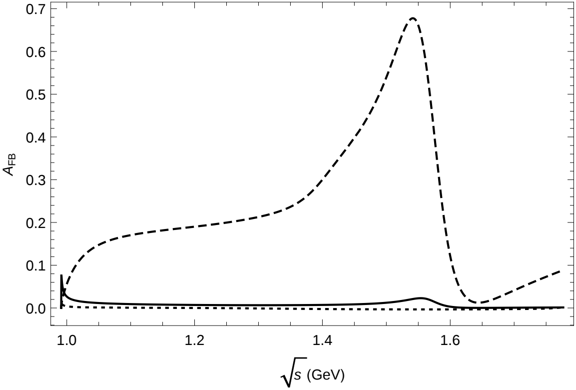


Figure: Forward-backward asymmetry for the decay $\tau^- \to K^- K^0 \nu_\tau$ in the SM (solid line), and for $\hat{\epsilon}_S = 0.1$, $\hat{\epsilon}_T = 0$ (dashed line), and $\hat{\epsilon}_T = 0.9$, $\hat{\epsilon}_S = 0$ (dotted line).

Spectrum

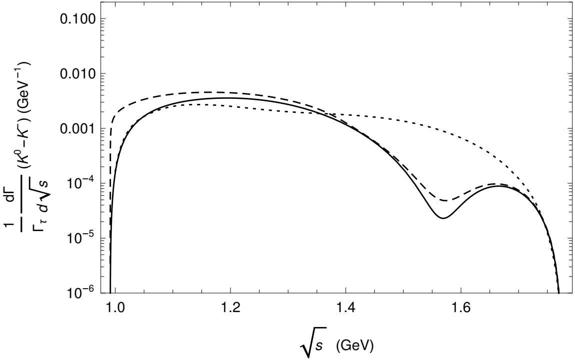


Figure: Invariant mass distribution for the decay $\tau^- \to K^- K^0 \nu_\tau$ in the SM (solid line), and for $\hat{\epsilon}_S = 0.1$, $\hat{\epsilon}_T = 0$ (dashed line) and $\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = 0.9$ (dotted line). The decay distribution is normalized to the tau decay width.